Optical investigation into the effects of suffusion in a granular medium

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Abstract: The current paper presents a novel experimental method which is able to capture the effects of suffusion by substitution of the fines in a sample by salt of a similar grain size. The setup is tailored to optically capture the change in soil structure behind a glass window in a plane strain strongbox using a digital camera. Subsequently, digital image correlation techniques have been used to quantify the structural change. The first model test shows promosing insight in the pseudo suffusion mechanism. The test setup therefore offers a valuable addition to permeameter tests.

Keywords: suffusion, 1g testing, PIV

1 INTRODUCTION

Suffusion is a process of internal erosion whereby fine grains are removed from a soil due to groundwater flow. This results in a change of hydraulical and mechanical material properties. A schematic overview is sketched in Fig. 1. Typically, a reduction of stiffness and strength is found. The latter reduces the stability of a soil structure or of a super structure founded on top. Suffusion is triggered in soils which are subjected to a large hydraulic gradient, i.e. levees or earth dams. A particular case is the WAC Bennet dam where the suffusion process leads to sink-holes. Suffusion is still an active research topic, e.g. Fannin & Moffat (2006), Muir Wood (2007)), however, most is focussed on characterizing the effects of suffusion in laboratory tests.

For this modified column or permeameter apparatuses are used to relate the removal of fine particles from a sample to the hydraulic boundary conditions, e.g., Bendahmane et al. (2008), Fannin & Moffat (2006), Skempton & Brogan (1994), Wan & Fell (2008). These experiments show that the critical hydraulic gradient, when suffusion occurs, not only depends on the experimental boundary conditions, but is also evolutionary (Marot et al. 2009). It is not sufficient just to monitor the hydraulic gradient and the outflow of fines from the sample. Visualization experiments potentially offer a better understanding of the physical mechanisms that occur in the sample.

The use of visualisation experiments to monitor deformations or particle movements in a granular medium is well estabilished, e.g. individual particles in a porous medium, granular flow, or deformation of soil near a pile (Ochiai et al. 2006, Spinewine et al. 2003, Slominski et al. 2007, White & Bolton 2004). The monitoring of the transport of fines within a soil matrix, however, proves to be very challenging, for which special image subtraction techniques are required (Rosenbrand 2011). The latter are introduced to overcome problems with particle tracking (the particle moves away from the wall) or loss of correlation, resulting from a change in image contrast of fines obscuring the matrix grains, in image correlation techniques.

In the current paper an alternative approach to study the effects of suffusion in a granular medium will be presented. In the new method the fine fraction in the sample has been replaced with salt (NaCl). Subsequently, during the experiment the sample is saturated and the salt will be dissolved. Hence, a change of particle grading is simulated by the outflow of the dissolved finer fraction. Compared to other suffusion experiments the unstable state is reached faster, and also the change in structure can be captured using particle image velocimetry (PIV). The method will not capture the fluid flow or the transport of salt directly, i.e. only the deformations of the soil matrix are captured.

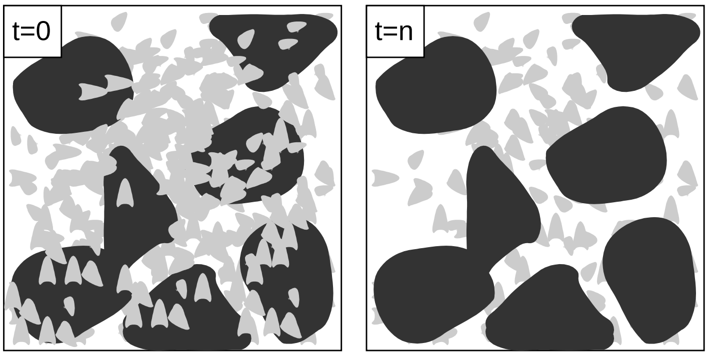

Figure 1. Schematic representation of suffusion, from Roosenbrand (2011)

2 EXPERIMENTAL SETUP

2.1 Sample

The sand and salt mixture consists of standard table salt (NaCl) with a grain diameter between 0 and 0.6 mm and a volumetric mass of 1180 kg/m^3 and sand with a grain diameter between 0.6 and 2.0 mm and a volumetric mass of 1800 kg/m^3. In the mixture, a mass percentage of 22.9% consists of salt. The remaining 77.1% is sand of which 25.64% with grain diameter 0.6-1.0 mm and 51.43% with a grain diameter 1.0-2.0 mm. A particle size distribution of the material is shown in Fig. 2. The total mass of the salt-sand mixture in the strongbox is 4.171 kg.

2.2 Mechanical Setup

The sand and salt mixture is placed in a strongbox which has 2 transparent windows. The inner dimensions are 402 402 20.3 mm (height width thickness). At the bottom of the container a geogrid with an internal height of 20 mm with non-woven geotextile on both sides is placed. This filter ensures a homogeneous upward flow through the sample. The total height of the sample comprised of sand and salt is 290 mm.

The sample is obtained by mixing the given masses of sand and salt and subsequently evenly pouring it in the strongbox using a funnel. After filling the strongbox the sample is somewhat densified with by tapping the box with a rubber hammer. Despite great care in the preparation, the differences in specific weight of the salt and the sand lead to the seggegration of sand and salt in the sample (e.g. Fig. 4A).

The inflow of water is at the bottom of the strongbox and is discharged through two outlets in the side walls at the top. The flow is driven by a constant head of 0.76 m and resulting in a flow rate of 6 ml/s. A sketch of the test setup is shown in Fig. 3.

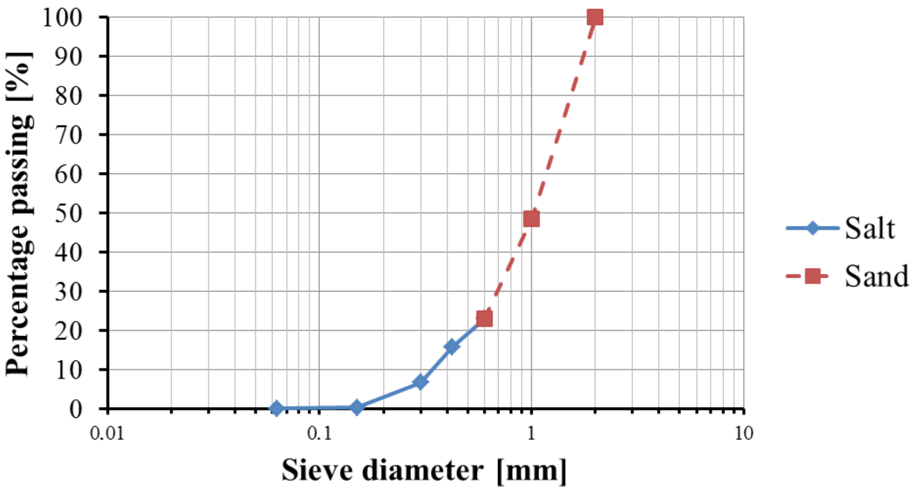

Figure 2. Particle Size Distribution; salt + sand

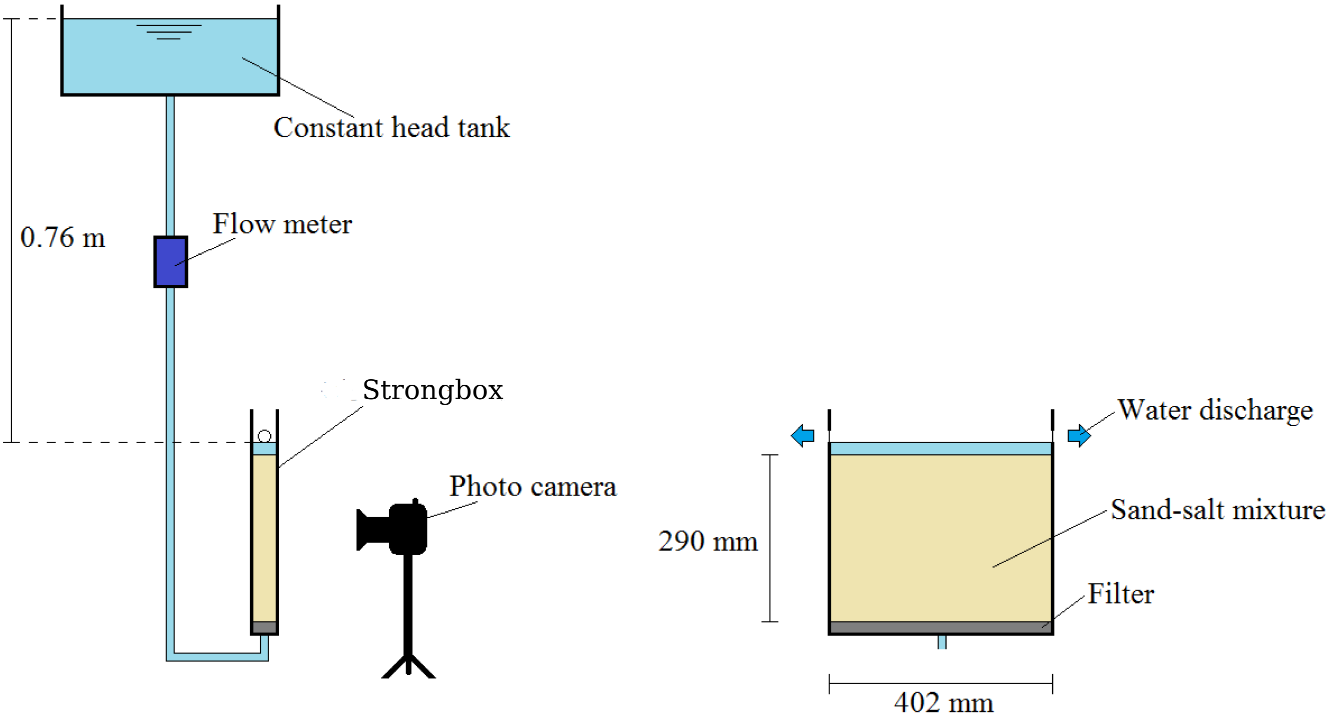

Figure 3. Mechanical Setup

2.3 Measurement Setup

The plane strain strongbox is illuminated by a high intensity fluorescent light source from one side. A Canon EOS 400D digital single-lens reflex (DSLR) camera, sensor size 3.28 cm^2, with a Canon EF 24 mm 1:1.4 lens is used for the image acquisition. The camera is triggered at an interval of 1 second. The obtained photos are pre-processed before the PIV analysis. First the photos are converted to 8 bit greyscale images and the region of interest cropped from the image. Subsequently, the contrast and brightness are mapped such that the full dynamic range is utilized. As a result the individual grains are better distinguishable. For the PIV analysis the open source toolbox JPIV has been used (Vennemann 2008). The correlation is performed for different time intervals between consecutive photos, i.e. intervals of 30 s and 120 s seconds.

3 RESULTS

The last photo of the experiment, shown in Figure 4B, is taken 16 minutes after the start of the water flow, for reference the first photo is shown in Fig. 4A. Darker areas indicate areas where during the experiment substantial amounts of salt have been dissolved and transported. The total displacements of the sand grains, as captured by the PIV analysis, are shown in Fig. 5. In this Figure the displacement field is an overlay on the last photo. Also, a close up of the zone with high activity is given, in this zone initially a large amount of salt was deposited. Generally, a positive correlation is found between areas with large displacements and areas where a lot of salt is dissolved. Or in suffusion terms: a zone with a high percentage of suffused fines results in instability with larger deformations in the remaining grain skeleton.

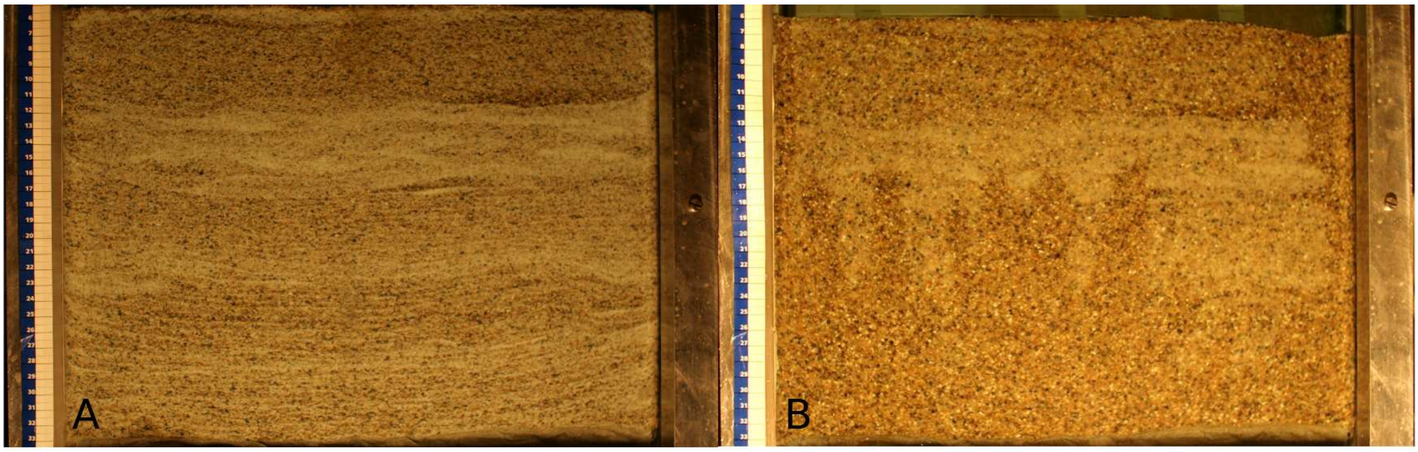

Figure 4. Sample before (A) and after (B) suffusion experiment.

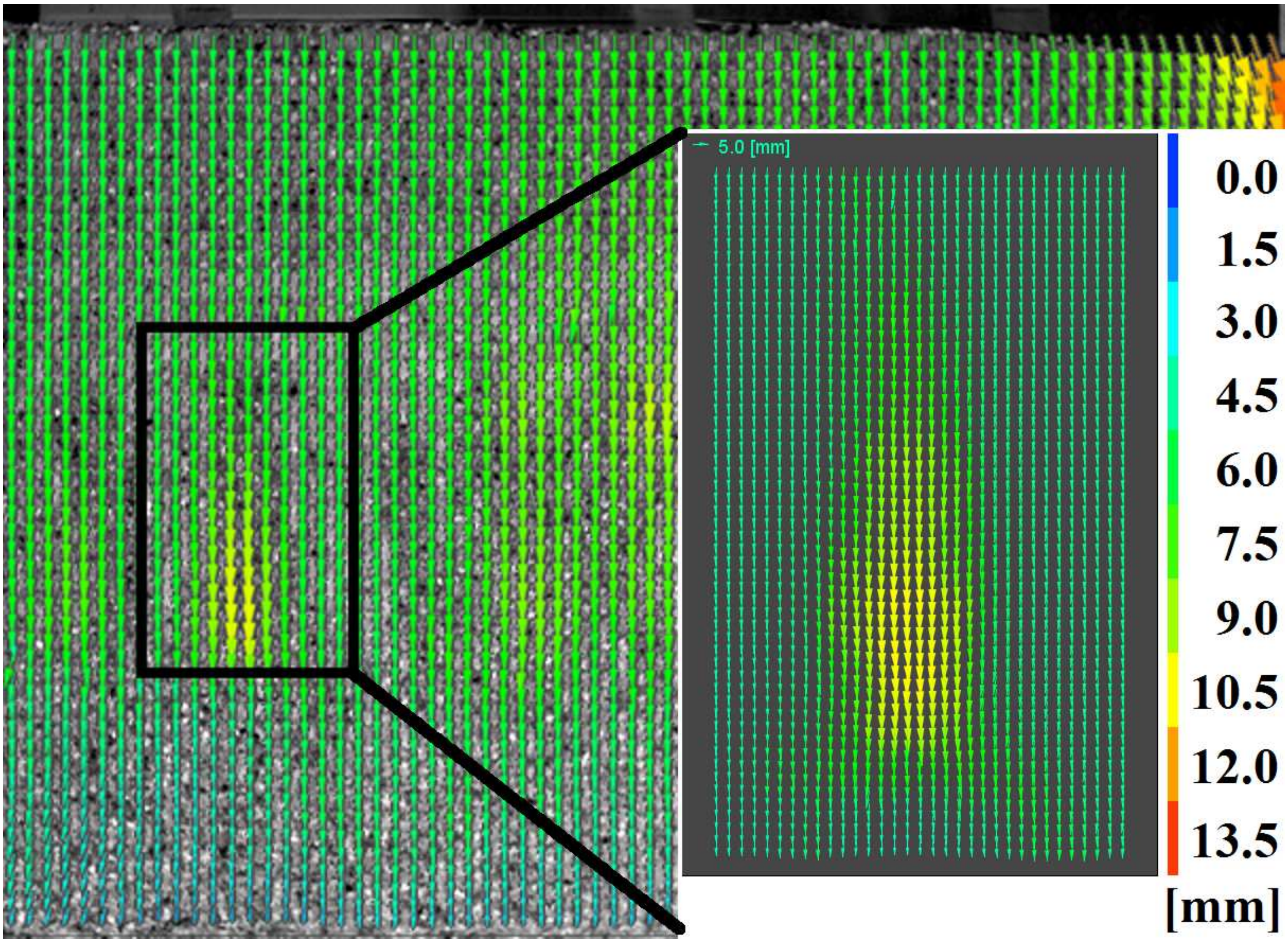

Figure 5. Total displacements in the sample after 16 mins of simulated suffusion.

The evolution of the deformations, resulting from movement of the grains, in the sample during the first three minutes of the test are summarized in Fig. 6. In this test stage the water level rises (represented in the Figure by two blue lines, the lower one is the water level at the start of the increment, the second line is the water level after the time increment has finished) until the total sample is saturated. This stage, also, was the most significant for the observed displacements. In the first three minutes a lot of activitiy is observed in the sample. Therefore, the presented displacement increments correspond to a time interval of 30 seconds. This Figure clearly shows that areas with relative large displacements are localized in the sample (see for example time interval 1 - 1.5 minute), and that in subsequent time intervals these larger displacements transgress upwards.

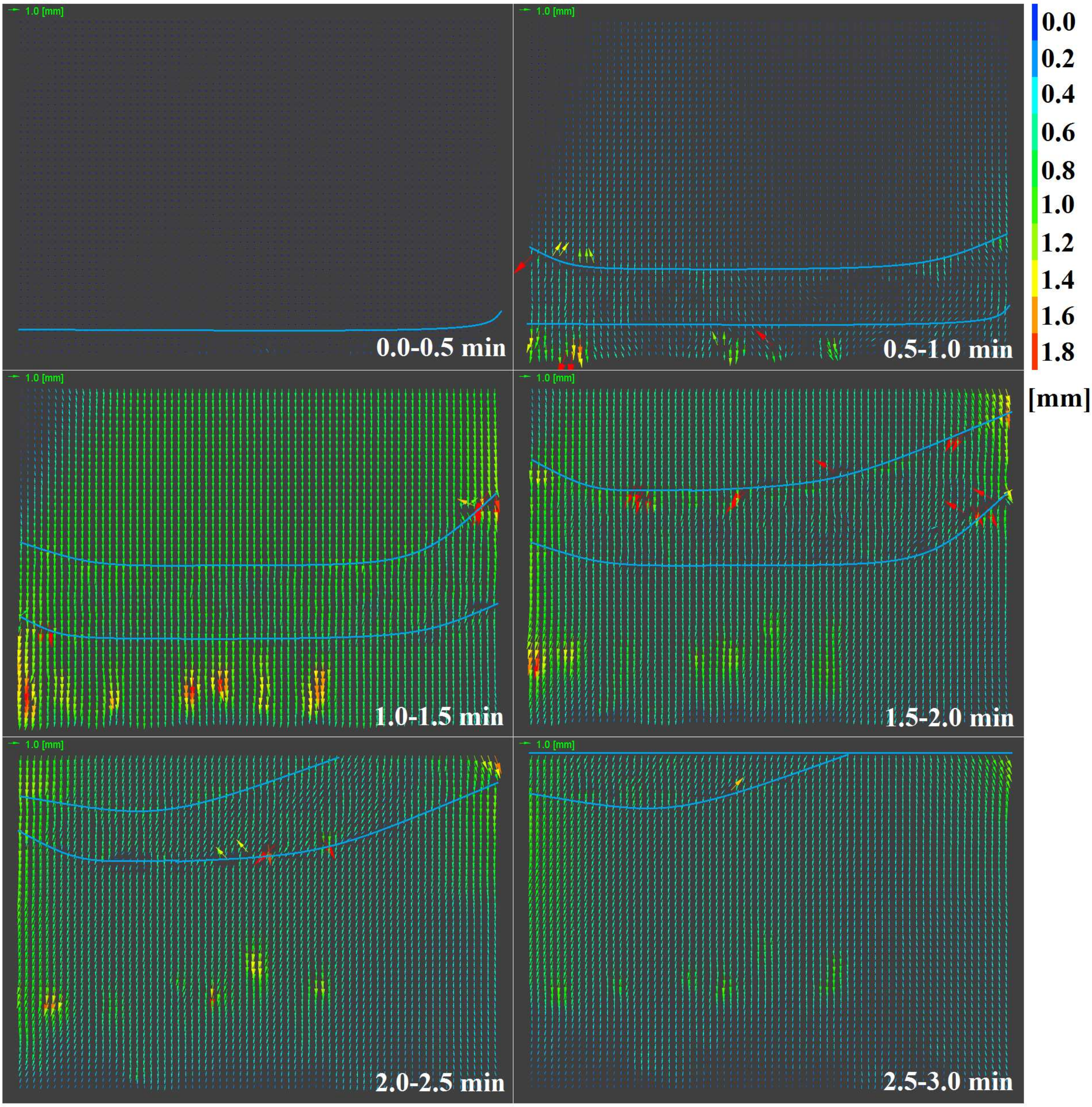

Figure 6. Evolution of the displacement increments in the sample for the first three minutes of the suffusion experiment during saturation of the strongbox; the two blue line represents the rising water table at the beginning (lower) and end (higher) of each 30 seconds time interval.

In Fig. 7 the subsequent 13 minutes have been shown with an increment of 2 min. The stream channels which are formed in the first three minutes now show less activity and new channels tend to form until these also become less active. This dynamic shifting of localised deformations appears to be a process of continuous collapse of the soil. It is interesting to note that the displacement in the soil skeleton between the initial and final water level of a 30 s observation period, Fig. 6, is smaller and more uniform than at the same location in the next increment, i.e. a delayed response of the displacements. It takes some time before the simulated suffusion from dissolving the salt is effective. The initial displacements are probably caused by the filling of the pores, resulting in small particle rearrangements in the grain skeleton.

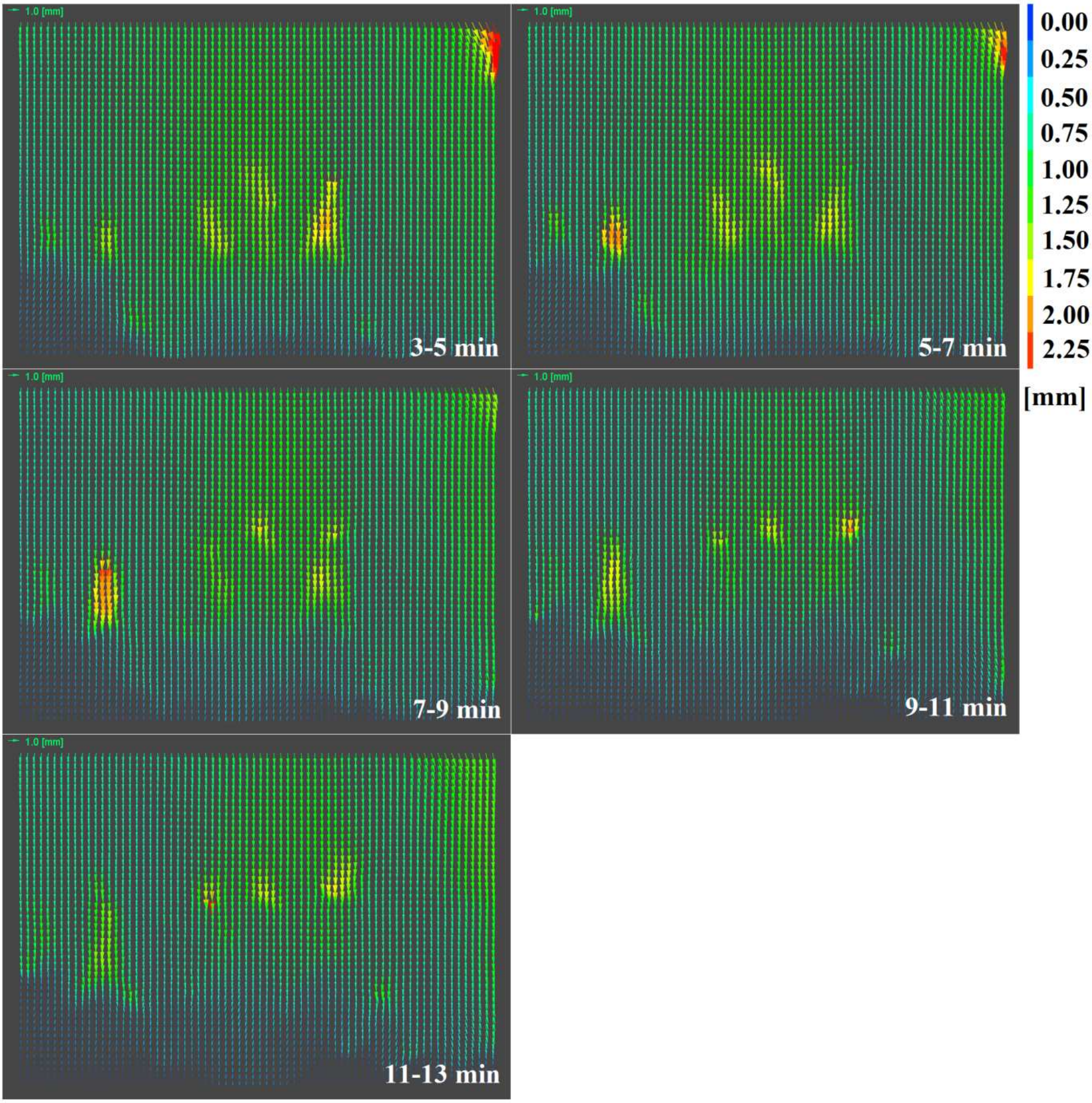

Figure 7. Evolution of the displacement increments in the sample for the last thirteen minutes of the suffusion experiment; the sample is fully saturated and a flow rate of 6 ml/s is maintained.

The localized displacements in one flow channel is studied in more detail in Fig. 8. The location of this channel and the total displacements, are already shown in Fig. 5. The size of the depicted zone which shows this channel is 64 mm x 100 mm. Again the incremental displacements are given for time intervals of 2 minutes. The results clearly indicate that between 3 and 5 minutes local failure of the soil takes place, and that in subsequent time intervals this failure transgresses upwards. This strengthens the observations on the larger field of view.

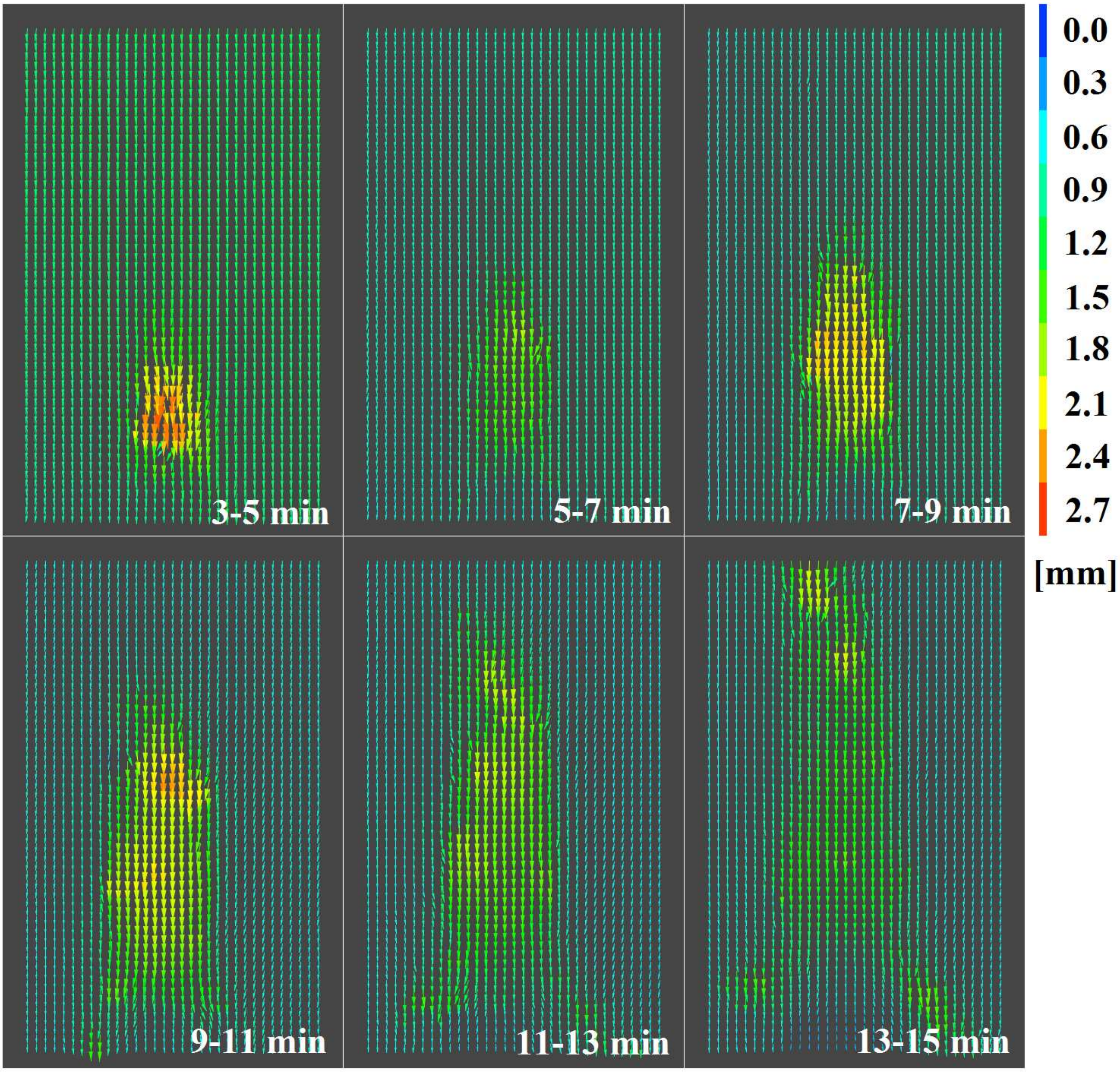

Figure 8. Evolution of the displacement increments in one flow channel within the sample, location and insert are shown in Fig. 5, for the last thirteen minutes of the suffusion experiment; the sample is fully saturated at a flow rate of 6 ml/s.

4 DISCUSSION

Image correlation shows that in the whole sample displacements take place. The surface displacement lie in-between 10 and 20 mm. However, in-situ suffusion is more subtle, so the soil skeleton should not deform dramatically during the process as initially, first the fines displace. In the current experiment the deformation in the skeleton of coarse particles is already quite significant. The results, therefore, need to be considered as a worst case scenario when progressive collapse in the final stage already iniates. For future experiments a better balance between the fine salt fraction and the coarse sand fraction and the particle sizes of each fraction needs to be found, as well as that seggregation, resulting from the significant difference in specific weights of the two materials, needs to be reduced during preparation. The latter, however, is quite difficult as a traditional dry raining/pouring technique will not address this problem sufficiently without dramatically reducing the dropheight. Raining in water, which potentially improves the quality of the prepared samples Poel & Schenkeveld (1998), is not an option when salt is used.

In the experiment was observed that locally more displacements are visible. These displacements are positively correlated with the decrease of the amount of salt. These local effects originate from a spatial inhomogeneity of the salt in the beginning of the experiment. Therefore, the permeability also will be different, as more permeable zones will form as more salt is dissolving. As a result these zones ‘attract’ the water, and again more salt will dissolve, which will result in an increased permeability. This leads to a positive feedback loop.

5 CONCLUSIONS

The aim of this research was to investigate the applicability of soluble salt particles as a subsitute for the fines fraction in a soil sample for the modelling of suffusion. The test setup is designed such that the change in stucture during the experiment could be monitored using optical techniques, i.e. capturing the displacements in the sample from digital images using digital image correlation. The first model test shows promising insight in the pseudo suffusion mechanism. However, the boundary conditions still need to be tailored to arrive at a more realistic simulation of suffusion, where the structural change is more gradually modelled. In the current tests only the final effects of suffusion have been obtained. The test setup, therefore, offers a valuable addition to permeameter tests.

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